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Virtual factory layouts from 3D laser scanning – A novel framework to define solid model requirements

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Abstract

In a world with increasing customer demands, manufacturing companies must develop and produce products more rapidly and adapt their production systems offline, to not disturb the ongoing processes. This creates a demand of using digital production development so that development can be performed in parallel with production. Virtual factory layouts (VFLs) are essential for companies in order to plan their factory layout and evaluate production scenarios. However, requirements for a VFL depends heavily on its purpose. For example, the requirements on a model for offline programming of robots are different from those on a model used to determine buffer locations. There is currently a lack of clear guidelines for how developed a VFL should be to fulfil said requirements, which contributes to unnecessary modelling time and variation in delivery quality.
This paper aims to put the actual demands and requirements of a VFL in focus. By adapting a Level of Development-framework for establishment of Building Information Models (BIMs) and connecting it to the purpose of VFLs, development of a framework for detail and functionality level of VFLs is enabled. Such a purpose-oriented framework will help to define delivery packages suited for different circumstances, which will provide the modeler with knowledge of how much detail and functionality a specific model should contain.
The increased clarity provided by the developed framework results in a clearer connection between expected result and actual output from a custom VFL project. Also, by connecting model properties or development to the model-purpose, the framework brings clarity and structure to a currently vague field. This provides means for a more efficient and accurate use of VFLs, which will support the rapid development of production facilities.

Keywords: layout; 3D-imaging; 3D laser scanning; virtual factory;

1. Introduction

With changing customer demands and global competition, manufacturing companies need to find ways of improving their processes without interrupting the ongoing production [1]. Process evaluation and improvement should therefore be made using virtual tools [2]. By examining facilities and processes virtually, time-consuming physical measurements and risks of human errors can be removed [3]. Effective development of improvements and decision making for a production system based on a virtual model requires a model that corresponds well enough to the actual system.

3D-imaging technologies, such as 3D laser scanning captures a production facility's spatial properties and opens the possibility to generate editable virtual factory layouts (VFLs) [2]. By 3D scanning a facility, an accurate, within a few mm, representation of the actual facility is captured as a point cloud [4]. To make this point cloud editable for improvement and evaluation, the point cloud should preferably be transformed to a solid model. Normally, this process consists of 3D-scanning, point cloud management, and manual 3D modelling. Yet, there are inconsistencies in how much the model should be developed during the modelling phase. This contributes to unnecessary, non-value adding modelling of functionalities

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that does not contribute to the purpose of the model. This paper aims to provide a framework for setting requirements on VFLs derived from 3D laser scan data. The framework defines and considers a functionality based level of development adopted from the field of Building Information Models [5], coupled with level of accuracy, and a novel level of recognisability concept developed for production system layout models.

2. Virtual factory concept

A VFL is the digital representation of an actual factory including, but not limited to, its building, machinery, and auxiliary equipment [1], [6]. The main goal with it is to support production evaluation and improvements while still producing high quantities and large variations of products.

An important application for organizations is to share ideas between different people and functions which can be made by using computer-graphics of manufacturing systems [7], [8]. Hence, a VFL is beneficial for communication and knowledge transfer since different people can take part of information without being present.

Another application of VFLs is to make time and cost savings by supporting offline layout design and simulation of factory operations [1], [9]. Evaluating design changes and process improvements offline increases time for planning and decreases time for realisation, which enables the real production to not be disturbed as much as if improvements were evaluated in the real production system. Further, a VFL enables execution of product and process development in parallel [10].

There are several advantages of using VFLs for improvement work. However, while creating a VFL, it is important to avoid design mistakes as well as measurement and modelling inaccuracies due to the cost it would bring [2]. 3D laser scanning is an accurate measurement technology which captures as-built data that can be used as reference for accurate modelling.

2.1. 3D laser scanning for production systems

By using a 3D laser scanner, a virtual representation of a real environment can be created [2]. The 3D laser scanner sends out laser beams that reflects back when it hits an object whereupon the distance the laser beam has travelled is measured [3]. Measurements are stored as points with XYZ-coordinates relative the scanner-position, creating a cloud of points that visualizes the real environment. The point clouds' density depends on the laser scanners' performance and the set resolution [11]. The 3D laser scanner can generally rotate 360 degrees around its vertical axis and 300-320 degrees around its horizontal axis, giving a large field of view. Also, many 3D laser scanners are today equipped with digital single-lens reflex cameras that capture images and maps them to the point cloud. This gives each point a specific colour resulting in a more realistic representation of the real environment.

By performing several scans, large areas and several sides of an object are captured. Although, the scans have to be merged together becoming a single point cloud with the same origin [12]. This merge-process, i.e. registration, can be made manually and automatically. Reference objects, commonly spheres or checkerboards, are added to the environment that is being scanned so that a software recognition algorithm can mark common targets and register the scans accurately. These reference objects also simplify manual registration since the user can identify and mark the reference objects easily.

2.2. Solid models and 3D laser scanning

CAD objects can be imported to a point cloud environment to support redesign of production systems [2]. This gives possibilities to put more time in the planning phase and reduces time for realisation. Also, it minimizes the risks of moving objects to places where they do not fit and secures that time is spent on tasks affecting the production system positively.

It is also possible to model solid objects using point clouds as reference. As modern laser scanners can capture 3D surface measurements in the mm accuracy range, the resulting solid models closely represents the real factory environment. There are much ongoing research on automating solid model generation from 3D laser scanned objects [13], [14].

Two possible ways of handling requirement definition of objects are Level of Development (LoD) and Level of Accuracy (LoA) [15], [16]. LoD focuses on reliability of models, which features they include and what purposes they are reliable for [15]. It is a framework for several objects and what they should include on a scale from 1 to 5. LoA focuses on tolerances, how much an object can differ within a certain tolerance, +/- values of accuracy [16]. The tolerances do not take in consideration certain object specific requirements or differences in positive versus negative tolerances. In the LoA framework described by [16], tolerances for both measured and represented accuracy are treated. Although, it is represented accuracy that is used and discussed in this article.

3. Data collection and framework development

The work presented in this paper adopts an action research inspired approach, where the current behavior is studied and understood, then changed and evaluated in iterative steps leading to an improved behavior [17]. The data collection was conducted through review and study of existing research and industry practices in the field. To explore industry practices, the processes of a consultancy company working with VFLs to industries was studied. Guidelines and best practices in the field of surveying and reverse engineering were included as a complement to the internal processes of the studied company. The findings were combined into a framework for modelling VFLs from 3D scanning data and tested at the studied company. The approach was evaluated and refined in collaboration with the experts to form the framework presented in section 4. Here follows a closer description of the interviews and framework development.

3.1. Focused interviews

Focused interviews were used to get an understanding of current practices, both within the studied company and in associated industry fields [18]. To map the current internal practices of the studied company, interviewees were chosen from both management and operational levels working on VFL projects within production industry. Furthermore, to broaden the view, interviews were conducted with external practitioners of reverse engineering from construction, infrastructure, and academia sectors.

The internal interviews provided insight regarding customer characteristics, common difficulties, and time-consuming steps in current methods. Customers participated in defining model requirements but modelers often faced difficulties in translating the requirements into a certain level of development or accuracy. This was said to result in varied quality of models, these variations were frequent both for models combined from different modelers and for models created by the same modeler. A lack of clear classifications in the model requirements led to modelers making a subjective interpretation of the various requirements and their relative importance.

The external interviews had one common finding; overdeveloping models, with regards to level of development and accuracy, is the main driver of time consumption in reverse engineering projects. In combination with the current lack of structured definition of model requirements, which were found in the studied company, a hypothesis was created that by properly assessing project characteristics, VFL projects could become far more effective and efficient.

3.2. Developing the framework

In developing the framework, existing projects were recreated according to available guides and shared knowledge at the studied company. Project characteristics were highlighted and structured as a workflow where input and output requirements were defined for the modelling process, several tests with different model definitions were conducted to evaluate the outcome. At first, the current process was carried out and evaluated, then the process was changed based on the findings from interviews, study of best practices, and further discussion with experts at the company. The changed process was then again evaluated and updated in steps to arrive at the final framework presented in section 4.

The studied company currently categorizes model requirements into three levels by work intensity; space obtaining, recognizability, and detailed. The first level only considers the space requirements of an object, whilst the second focuses on the recognizability of the object, and the third focuses on accuracy of the representation. The three categories are hard to separate from each other. E.g. at the development-level space obtaining, an object can be represented by a block, but the modeler still has to make a judgement on appropriate tolerances, as well as adding recognizability features, e.g. naming, in order for the receiver to know which object it illustrates. Similarly, both the recognizability and the detailed categories require a combination of features from development, accuracy and recognizability to make sense. This led to the understanding that a more diverse and differentiated implementation of model requirement categories was needed.

By further investigating company's customer characteristics, a set of use cases, or purposes, for virtual layout projects were identified. The development characteristics were inspired by the BIM and LoD concepts, with focus on what the end-product should be valid and reliable for. The accuracy characteristics were investigated by looking into tolerance setting in development projects as well as the Level of Accuracy structure from USIBD [16]. To define the more abstract criteria of recognizability, focus was put on potential receivers of the models and what, in general, should be required for the observer to interpret the model contents.

Different recognizability features such as color, significant object features, naming, etc., were used to connect observer requirements to actual features. Depending on the observer, different features were preferable to asses recognizability, which resulted in proposed feature combinations rather than increased levels of recognizability to assess the right level of recognizability for each specific receiver. Standard objects frequently occurring in factories, were modelled to be used as reference objects. These objects were combined with explanatory descriptions to guide the modelers regarding which features are most important and which ones are not contributing at certain level of recognizability.

4. Framework to define solid model requirements

This chapter aims to describe a structure for how to tackle uncertainties in transforming factory layout point clouds to solid models of project specified properties and quality. With the means of LoD, LoA and Level of Recognizability (LoR), a project purpose should be able to define in properties and quality (see Fig. 1). By combining features or levels from these three classification areas, clarity should be provided to the receiver of a project and the resources executing the project. This can result in decreasing uncertainty issues of over-development and misalignment in customers and suppliers view of the expected output.

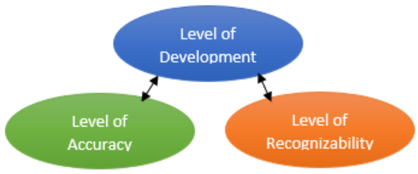

Fig. 1. Correlation between Level of Development, Level of Accuracy and Level of Recognizability.

4.1. Purposes of having a virtual factory layout

By looking into some frequent issues to handle in production engineering, purposes of VFL projects can be assessed. In this section, focus is put on three areas, where a virtual replica of the factory can provide means to tackle these issues. During the interview study, following areas were found to be recent purposes of initiating VFL projects; Knowledge transfer, Layout management and Simulation.

The three areas cover potential usages of VFL, from knowledge transfer and idea sharing [7], [8], to offline layout design and simulations of potential new layouts and cells [1], [9]. Further, all three of them can be derived into sub-areas, where knowledge transfer can be anything from general layout description to specific machine information. Layout management can be divided in new factories or changes in existing ones, whilst simulations can be divided into flow, 2D movement, 3D movement or robot simulation. This variation in purposes, puts different requirements on the means necessary for defining them, where the three classification areas aims to bring clarity. However, most of the purposes for a knowledge transfer project aims to provide as-is representations as means for communication, which can be done solely by the point cloud. The examples of this article will therefore only focus on sub-areas from Layout Management and Simulation, where Layout Change Management and 3D Motion Study will be exemplified.

4.2. Level of Development

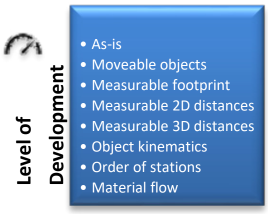

Fig. 2. Features included in the classification area Level of Development.

To make sure that a virtual object can be used for its specific purpose, its purpose has to be translated into what functionality to include. The description of an objects functionality is what Ikerd [15] calls Level of Development (LoD) for BIM, which can be adapted to work for VFLs as well. There are numerous functionalities, i.e. LoDs, which can describe what a virtual object can be used for. However, the LoDs described in this framework are limited to represent the three model purposes from section 4.1; Knowledge transfer, Layout management and simulation. The LoDs used in this framework are presented in Fig. 2.

Connecting Layout Change Management to the LoDs in Fig. 2, would require measurable footprint for the user to measure between objects to secure a flawless rearrangement of objects. This requires clearly defined areas and corners of the objects so that the user easily can choose areas and corners to measure between. Also, the user would want to move the objects to visualize how the new layout would look, which makes it necessary to include moveable objects. Making an object moveable means that it is located as its own part inside the factory assembly so that it can be rearranged in relation to the other objects.

Regarding simulation of production systems, 3D Motion Study will be exemplified to illustrate how the use of LoDs can define requirements for a specific simulation purpose. In this article, the 3D Motion Study is defined as a static environment where an operator or robot can be inserted into. It requires 3D measurability of all objects related to a potential operator or robot task, as well as objects that might interfere. 3D measurability should provide means to measure required movement distances for tasks, which standard times can be based upon.

4.3. Level of Accuracy

Fig. 3. Exemplified Level of Accuracy options.

Regardless the purposes of creating a VFL, defined accuracy is required, these levels could be chosen from Fig. 3. In Layout Change Management it is required to know the accuracy of the outer dimensions of the objects one want to align, otherwise the user will not know what the VFL is valid for. This would generally require a medium tolerance of space obtaining measures, whilst a very coarse tolerance for others. In simulation of 3D operator movement, a certain accuracy is required to make correct assumptions of time required for the movements, demanding a fine tolerance for these measures. There are already tools for handling general measures such as ISO-2768 and USIBD LoA documentation which deeper handles tolerances [16], [19], combined with manufacturing documentation tools such as surface profile tolerances, LoA should be able to define from already existing means [20].

4.4. Level of Recognizability

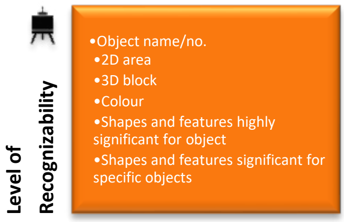

Fig. 4. Features included in Level of Recognizability.

For a VFL to fulfil its purpose, it is a necessity that the receiver of the layout understands what it illustrates. Since the experience and knowledge of viewers differ, the requirements on the layouts differ as well. Production engineers well familiarized with the facilities, can recognize objects by few means while consultants or other persons less familiarized with the facilities may require additional shapes or features, and sometimes even descriptive texts.

In this article, LoR has been designed to support practical use, where focus is to support the modelers with visual aids and to show the receivers what visual recognizability they can expect from the model. The LoR is in Fig. 4 presented by words, where each bullet point is related to a feature making the object more recognizable. As a complement to Fig. 4, reference models of frequently occurring objects such as material racks, work tables, milling machines, etc. could be described by a couple of pictures and text describing how the model relates to the chosen features. This will provide both the project initiator and modeler with what to expect in terms of recognizability of an object.

The first example, describing how to use LoR, in Fig. 5 (a) is suited for a receiver well familiarized with the production system that wants to make changes to an existing factory layout while the second example in Fig. 5 (b) is adapted for performing a 3D motion analysis to see how humans can interact with the objects.

Fig. 5 represents a portable scanning station, used for Layout Change Management and 3D Motion Study, where (a) is assessed with the features 3D block and colour. Combined with a BOM, the colour should be enough to define which scanning station it relates to. Fig. 5 (b) is presented by other LoR features, here the significant shapes and features are used to describe the specific object. Since 3D Motion Study is connected to the LoD requirement of 3D measurability, the LoR focuses on all parts valuable for the 3D study, e.g. barcode scanner, barcode booklet, etc., since just knowing it is a portable scanning station is not enough. In this case recognizability focuses on all parts combined with a task in the motion study.

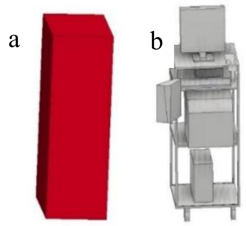

Fig. 5. (a) 3D block model with colour; (b) Model including shapes and features significant for specific objects.

4.5. Combine Level of Development, Level of Accuracy and Level of Recognizability

A single classification area says little about the reliability of the whole project. It is first when all three classification areas are combined that it is possible to say what the model can be used for and what is required by the receiver of the model. Without knowing the recognizability of an object it is not possible to determine what is required by the observer to understand the object. Furthermore, it is required to know the accuracy level in order to know the validity of measures obtained from a layout. When it comes to LoD it is perhaps even more obvious, if the model does not have the features needed to fulfil the purpose of the VFL, the purpose will not be achieved.

Combination of classification areas can be defined once in a project or for separate areas or objects of a factory. VFLs are commonly used for several purposes, 3D motion studies might be performed on a cell or production line, whilst the rest of the factory only will be used for layout purposes. It could therefore be suitable to have general project requirements of a Layout Change Management project, whilst the specific cell or line has requirements combined with 3D Motion Study. However, depending on amount of different applications of the VFL, it might be wise to limit each project to a manageable amount of variations. Otherwise, the time gained from not over-developing models, can be lost in additional time for defining and keeping track of all conflicting requirements.

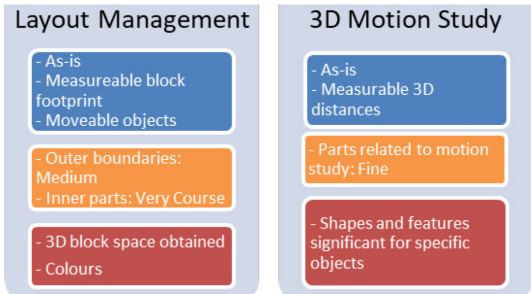

Fig. 6. Potential examples of combination of classification areas for Layout Management and 3D Motion Study purposes .

To clarify how the classification-areas can be combined, an example of two different packages is presented in Fig. 6. The packages are Layout Change Management and 3D Motion Study, and consist of different LoDs, LoAs and LoRs. For the Layout Change Management package, objects are presented in current position and with ability to be moved and measured from. The accuracy is set suitable to the purpose and models can be recognized from colours and position with support of a BOM (see Fig. 7). Similarly, the 3D Motion Study purpose can be defined from different features from the three classification areas. Objects needs to be located in their as-is positions with measurable 3D distances, with a fine accuracy of the ingoing parts to accurately estimate time of movements and having all features used in the study recognizable. In Fig. 5 (b) it is visible how the receiver of the model can recognize and measure distances between barcode scanner, barcode booklet, printer and keyboard.

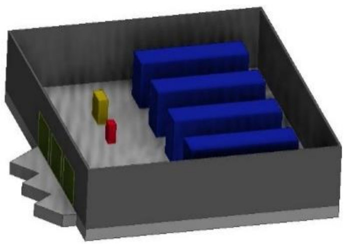

Fig. 7. Example of Virtual Factory Layout aimed for Layout Management.

5. Discussion

This chapter aims to discuss strengths and uncertainties of the proposed framework, as well as provide a basis for further research within the area of defining clear guidelines for VFL-modelling from 3D laser scanned data.

The combination of LoD, LoA and LoR has its major strength in handling difficulties of accurately describing what is required of a virtual object to fulfil certain purposes. However, the classification areas LoD and LoR are rather a set of features than hierarchical levels. The reason for this is simply to provide a framework that can be practically useful, both for modellers and end-users. Therefore, benefits were seen in using reference objects describing LoR, providing the modeller with visual guidelines of how detailed objects should be modelled.

Another uncertainty is the connection between LoD and LoA. This framework does not consider how the LoD-LoA-relation should be assessed without the need of setting specific LoA for each feature of an object. For example, when planning a layout there might be no value in knowing exact position of parts within a workstation, but the outer dimensions and material output could require tight tolerances to judge possibilities of aligning stations of a line as desired. When choosing LoD for a project like this, it is needed to know whether a specific LoA has to be chosen for this feature or if there is a general LoA for the whole project, including different tolerances for different features.

How to apply the proposed framework depends on if VFLs are products your company sells or if you create a VFL only once. Even with clearly defined classification areas and features, it might be tricky to choose the optimal classification-combination for each model purpose. Yet, even more evident is that it will be difficult for a modeller to successfully model according to numerous different custom specifications. For firms focusing on selling VFLs, it would be highly beneficial to pre-define packages for certain purposes as exemplified in section 4.5. This would clarify requirements of each package and by that simplify for the modellers due to less variations between deliveries. Also, it would clarify the customers' view on what they can order and expect to get delivered. Although, if a VFL is created once, it might be beneficial to choose features and levels of the classification-areas specific for your project so that the virtual layout fulfils all your needs.

Finally, the authors would like to highlight some areas where further research is needed to develop the proposed framework. First, the presented framework is limited to research and case study findings made. To create a more extensive framework, including more potential features, further thorough investigation is needed. Also, it would be of interest to examine if there are other potential purposes of obtaining a VFL and dig deeper into these areas. These investigations could result in a framework covering a broader scope and increased applicability.

Secondly, the presented framework only considers modelling of VFLs from 3D scanned data and the accuracy between these two states. However, another aspect to consider is the measured accuracy and the coverage of the scans made. To make sure that the VFLs represents the actual factory layouts as accurate as possible, the 3D scanned data has to be captured with an accuracy that is within the tolerance-limits and has to be accounted for when setting tolerances for represented accuracy. Also, it is necessary to make sure that concerned objects are fully captured so that the modeller can make a reliable estimation of how the objects look like in reality. Therefore, it would be beneficial to create a framework inspired by USIBD [16], handling measured accuracy.

Lastly, since this framework aims to reduce superfluous modelling time, modelling can be avoided entirely. E.g. if the purpose of a VFL is to transfer knowledge it can be enough to use a point cloud representing the actual factory since it fulfils LoD, LoA and LoR requirements if the scans are performed carefully. This eliminates risks of accuracy deviations while modelling and delivery time can be heavily reduced.

6. Conclusion

The best way to reduce lead time while modelling VFLs is to model just enough detail for the VFL to fulfil its purpose. Furthermore, the help of clear guidelines while modelling a VFL may reduce the gap between expected and actual result. Hence, the authors propose a purpose-oriented framework consisting of three areas; LoD, LoA and LoR, assessing functionality, accuracy and visual recognizability, respectively. Composed, these three areas are supposed to describe the minimum development required of a VFL to fulfil a certain purpose as well as close the gap between expected and produced result.

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